

VOLUME CHANGES ATTENDING HYDRATION OF QUENCHED MAGNESIUM SULFATE BRINE: THE TECTONICS OF GANYMEDE'S SULCI, D.L. Hogenboom¹, J.S. Kargel², M.L. Reiter¹, and Y.N. Khor¹; ¹Dept. of Physics, Lafayette College, Easton, PA 18041 (email: hogenbod@lafax.lafayette.edu); ²U.S. Geological Survey.

Overview. The phase behavior of magnesium sulfate–water at elevated pressures may have important applications to the understanding of tectonic features on Ganymede. Fractional volume changes accompanying crystallization, melting, hydration, and dehydration of $\text{MgSO}_4\text{--H}_2\text{O}$ mixtures observed in the laboratory are as large as the global expansion proposed to explain extension in the grooved terrain. Expansion attending phase changes in thick cryovolcanic deposits offers an alternative to global expansion as a cause of fracturing in Ganymede's sulci. We report phase and volume changes from 3 data runs on a sample of 35.76% MgSO_4 , equivalent to $\text{MgSO}_4\cdot 12\text{H}_2\text{O}$ (henceforth MS12) at pressures of 96, 110, and 250 MPa.

Experimental. This work is the most recent in a series of experiments at Lafayette College in which the phase diagrams and phase densities of planetologically important systems have been studied at temperatures down to 130 K and pressures to 400 MPa. Our apparatus and the techniques have been described previously [1]. The same publication contains results of an earlier study of the system $\text{MgSO}_4\text{--H}_2\text{O}$ at concentrations of 15.3%, 17%, and 22% MgSO_4 (by mass). The sample of 35.76% MgSO_4 used in this study had a mass of 1.817 g. Unlike the earlier samples, this one was contained in a thin-walled teflon capsule that better enabled exploration of the subsolidus region. A recent description of the capsules and their use in studying the ammonia–water system is given in [2]. For reference, we provide a phase diagram for the system $\text{MgSO}_4\text{--H}_2\text{O}$ at a pressure of 1 atm (Fig. 1).

Results. Raw data from our three latest runs are shown in Figures 2–4. Transducer voltage is almost linearly related to sample volume, so a drop in voltage signifies an increase in sample density. All three runs started with the sample in a phase field where it ought to consist of a mixture of $\text{MgSO}_4\cdot 7\text{H}_2\text{O}$ (MS7) and liquid solution of ~26.5% MgSO_4 . Initially the sample was visibly a slurry of crystals and liquid. As we cooled the sample for the run shown in Fig. 2, the first downward dip from the straight cooling curve gave an indication that MS7 had started to hydrate to MS12, as it should according to the phase diagram [1]. Although MS12 is not as dense as MS7, the hydration of MS7 consumes low-density ice, causing a net density increase, as observed (voltage decreases).

When we repeated this run at only slightly higher pressure, we obtained a comparable result overall, but there were marked differences (Fig. 3). As we cooled the sample, the first additional solid phase to crystallize apparently was water ice I, rather than MS12; evidence for MS12, the stable hydrate at low temperatures, was not obtained until later in the run. We infer that after rapid formation of ice, the sample consisted of a meta-stable mixture of ice I and MS7 with the possible addition of MS12 and liquid (equilibrium predicts pure MS12).

Figure 3 shows substantial reproducibility of various transitions. For instance, the smoothly rounded curve near

259 K was repeated three times and had a similar shape during cooling and warming, and each time this transition preceded a period of thermal invariance (probably peritectic melting), yet the first warming produced a rounded curve offset from the following repetitions of this curve. The cause of this discrepancy and the differences between the runs shown in Figs. 2 and 3 seems to be sluggish hydration; when the sample ought to consist of pure MS12 sometimes it actually consists of varying proportions of ice, MS7, MS12, and perhaps liquid. We think that this mixture gradually tends toward an equilibrium composition (pure MS12) by slow hydration of MS7, which consumes metastable ice. We do not fully understand what controls initial crystallization, why metastability varies between runs or how sensitively the hydration rate depends on P and T.

Volume change of hydration: Applications to Ganymede

The sluggish hydration kinetics of the reaction $\text{MS7} + 5\text{H}_2\text{O} \rightarrow \text{MS12}$, noted earlier by Kargel [3] in experiments at 1 atm, is in contrast to MS7, which forms far more readily. The new results indicate that at least a day is required for $\text{MgSO}_4\text{--H}_2\text{O}$ mixtures to approach equilibrium hydration even at relatively warm temperatures and more time at colder temperatures. Since lab experiments commonly are conducted over periods of about a day, metastability can explain inconsistent data reported by various laboratories ([1] and [3]).

At the low temperatures of Ganymede's surface, equilibrium hydration of MgSO_4 may still occur on a geologic timescale. Brine flows erupted on Ganymede might freeze and equilibrate much as we see in our experiments. At first the flows might quench to a meta-stable state. A eutectic flow approximated as 17% MgSO_4 might then form a metastable mixture of about 65.2% ice I + 34.8% MS7 (by mass). Over time it could revert to an equilibrium assemblage of about 52.5% ice + 47.5% MS12.

A previous paper [1] gave the densities of MS12, MS7, and ice as 1.50, 1.68, and 0.917 g cm^{-3} , respectively, at low pressure and at temperatures near the peritectic. For a eutectic composition (17% MgSO_4) the hydration of MS7 to MS12 would be accompanied by a net 3.16% decrease in the volume (or increase in density) of the mixture. This is comparable to the global expansion required (about 2%) to explain the grooved terrain on Ganymede [4]. Since the tectonic effects of global expansion would locally be similar to the effects of crustal contraction over an interior of constant radius, we find that hydration of quenched magnesium sulfate brine flows is capable of explaining the magnitude of extension in the grooved terrain. Other mechanisms are reviewed by [4].

This mechanism requires the accumulation of a thick cryovolcanic sequence of quenched flows followed by their reversion to a stable state. This can explain intense fracturing of Ganymede's sulci. The amount of extension and the depth and spacing of faults would correlate with the

MAGNESIUM SULFATE-WATER: D. L. Hogenboom et al.

thickness of the quenched cryovolcanic deposits that undergo hydration, and they might vary locally according to the heat flow that may help drive hydration. This mechanism will not work if re-version to a stable assemblage is more rapid than the accumulation of a thick cryovolcanic pile, or if hydration to MS12 and attendant volume contraction requires longer than the Maxwell Time for creep relaxation of extensional stress ($\sim 10^7$ - 10^8 years according to [4]).

We conclude that density changes associated with hydration of quenched cryovolcanic deposits may offer another plausible mechanism accounting for post-depositional faulting of Ganymede's sulci.

References. [1] Hogenboom, D.L., J.S. Kargel, J.P. Ganasan, and L. Lee, 1995, *Icarus*, v. 115, p. 258-277. [2] Hogenboom, D.L., J.S. Kargel, G. Consolmagno, T.C. Holden, L. Lee, and M. Buyyounouski, 1997, *Icarus* (in press). [3] Kargel, J.S., 1991, *Icarus*, v. 94, p. 368-390. [4] Squyres, S.W. and S.K. Croft, 1988, in: *Satellites* (J.A. Burns and M.S. Matthews, Eds.), pp 293-341.

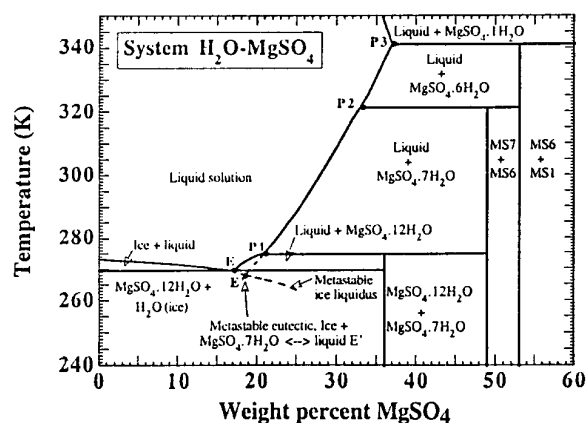


Figure 1. Phase diagram of system MgSO_4 - H_2O , 0.1 MPa.

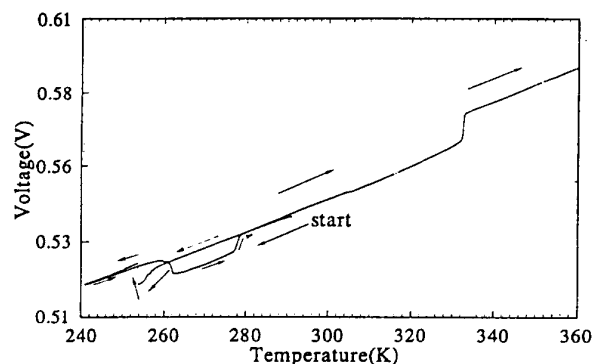


Figure 2. Run on 35.7% MgSO_4 , 96 MPa.

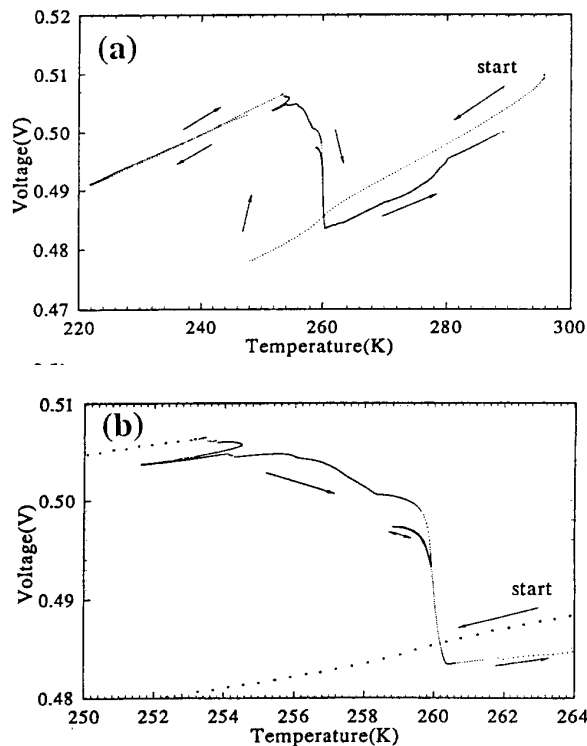


Figure 3. Run on 35.7% MgSO_4 , 110 MPa. (a) entire run, (b) expansion of region near 260 K.

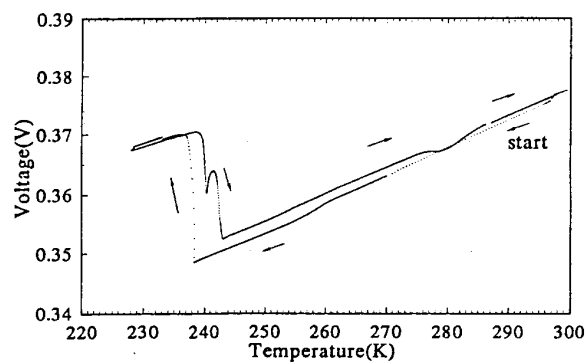


Figure 4. Run on 35.7% MgSO_4 , 250 MPa.